UCRL-JC-123033
PREPRINT

Precision Optical Aspheres for Extreme Ultraviolet Lithography

D. R. Kania, D. P. Gaines, D. S. Sweeney
G. E. Sommargren, B. La Fontaine, S. P. Vernon
Lawrence Livermore National Laboratory
Livermore, CA 94551

D. A. Tichenor, J. E. Bjorkholm, F. Zernike
Sandia National Laboratories
Livermore, CA 94551

R. N. Kestner
Tinsley Laboratories
Richmond, CA 94806

This paper was prepared for submittal to the
40th International Conference on Electron, Ion and
Photon Beams and Nanofabrication
Atlanta, GA
May 28-31, 1996

May 1, 1996

Lawrence Livermore National Laboratory

DISCLAIMER

UCRL-JC-123033

Precision Optical Aspheres for Extreme Ultraviolet Lithography

D. R. Kania, D. P. Gaines, D. S. Sweeney, G. E. Sommargren,
B. La Fontaine, and S. P. Vernon
Advanced Microtechnology Program
Lawrence Livermore National Laboratory
Livermore, CA 94551

D. A. Tichenor, J. E. Bjorkholm,* and F. Zernike†
Sandia National Laboratories
Livermore, CA 94551

R. N. Kestner
Tinsley Laboratories
Richmond, CA 94806

Abstract

We have demonstrated significant advances in the production of aspheric optics for extreme ultraviolet lithography. An optic has been fabricated with an aspheric departure of 1.5 μm, a figure error of 0.7 nm rms and a nanoroughness of 0.25 nm rms. Further improvements are required in the figure and nanoroughness to reach high throughput and near diffraction limited performance in an EUVL system.

*Present address: Intel Corporation, Santa Clara, CA.
†Consultant

Introduction

The optical elements for Extreme Ultraviolet Lithography (EUVL) must be fabricated with unprecedented figure accuracy and surface quality. These stringent demands are a result of operating at a wavelength of 13 nm. The benefits of operating at this short wavelength are small numerical aperture (NA) and large depth of focus while printing at small critical dimensions (CD). For example, a system operating with a NA of 0.1 printing at a CD of 0.1 μm will have a depth of focus of greater than 1 μm at the wafer. These characteristics make EUVL an attractive option for the 0.1 μm generation of lithography.

EUVL optical systems must be reflective because of the large optical absorption coefficient of all materials in this wavelength range. High reflectivity can only be achieved by coating the optics with a multilayer coating. For operation at 13 nm, a 40 bilayer coating is used. Each bilayer consists of 3 nm of molybdenum and 4 nm of silicon. These coatings have achieved a reflectivity of greater than 65%.[1]

Commercial lithography demands high throughput which constrains the design of the optical system, the number of reflections must be minimized. Each additional reflection in the optical system reduces the throughput by at least 30%. Therefore, a premium is placed on achieving high reflectivity and minimizing the number of reflections in the system. The reflectivity is degraded with increasing substrate surface roughness which causes energy to be lost to large angle scatter. Spatial frequencies smaller than 1 μm define the surface roughness. We will use the term *nanoroughness* in this paper to describe this quantity.

The requirement for a minimum number of optical elements and for low distortion imaging dictates the use of aspheric optical surfaces. Current designs need three to five reflections from aspheres to achieve imaging characteristics suitable for 0.1 μm lithography. The aspheric departures across the clear aperture are typically a few microns. Each optical element must be figured to subnanometer accuracy to achieve near diffraction limited performance.

Figure requirements

For near diffraction limited imaging, the Maréchal criterion[2] dictates that the maximum tolerable rms wavefront error is $\lambda/13.5$ for the entire system. The relevant spatial frequencies defining the optical figure vary from the size of the clear aperture to approximately one millimeter. Assuming that the wavefront error associated with each optical element is uncorrelated, the wavefront error of each optical element in a system adds in quadrature. The surface figure tolerance for an individual element is compressed by a factor of two, the square root of the number of element for a four element system. The effect of figure irregularities is doubled upon reflection resulting in an additional factor of two tighter tolerance on the figure accuracy. For a 4 reflection imaging system, the net effect is that each optical surface must be accurate to $\lambda/56$ or 0.25 nm rms. We recognize that the Maréchal criterion is a necessary, not sufficient, condition for lithography. Tighter figure tolerances may be required in a practical lithographic system.

The fabrication of an optical surface to subnanometer accuracy requires metrology with this capability. The phase shifting point diffraction interferometer (PSDI) developed by Sommargren[3] has an accuracy of 0.6 nm rms. The interferometer employs a phase shifting interferometer with a spherical reference wave generated by a small aperture or optical fiber. Since the reference wavefront is spherical, the fringe density can be large in some regions of the clear aperture for aspheric surfaces. High fringe density results in reduced measurement accuracy. Multiple data sets are used to circumvent this problem. Additional data sets are taken after translating the optic along the axis of illumination. The movement of the optic moves the area of low fringe density aross the clear aperture. A sufficient number of data sets are taken to yield low fringe density high accuracy data over the entire clear aperture. These data are stitched together in software yielding an accurate map of the reflecting surface.

Nanoroughness requirements

The effect of nanoroughness on the reflectivity of the multilayer coating is demonstrated in Figure 1.[4]

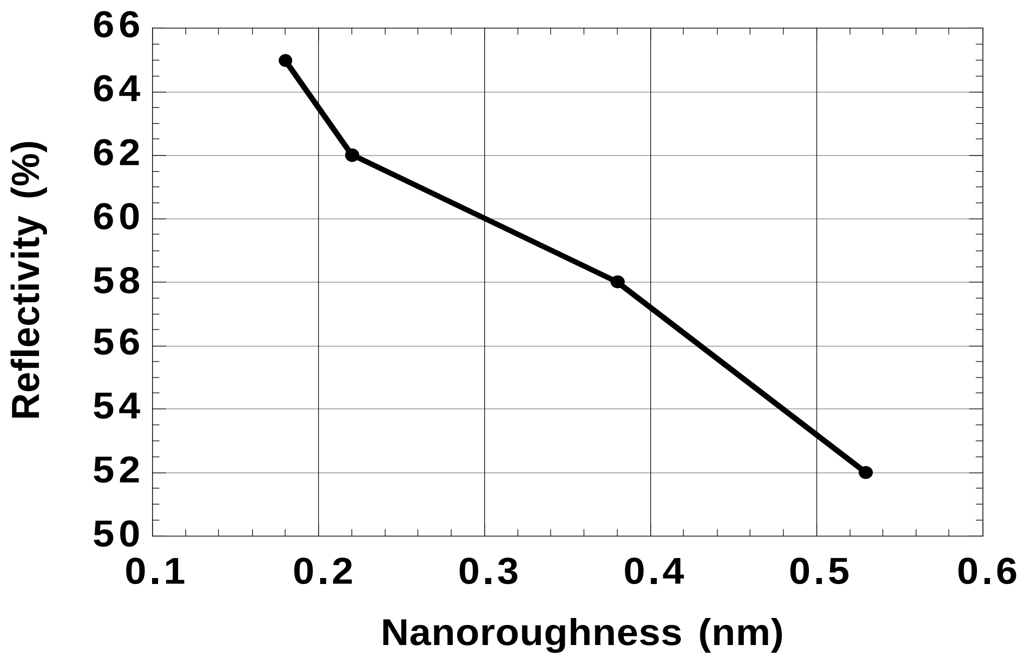

Figure 1: Multilayer reflectivity at 13 nm is a decreasing function of nanoroughness. The molybdenum-silicon multilayers were grown on fused silica substrates.

Increases in the nanoroughness significantly reduce the reflectivity and the system throughput. The throughput of an n mirror system scales as R^n, a 5% decrease in reflectivity or a nanoroughness of 0.3 nm rms will reduce the throughput of a four reflection imaging system by 25%. Nanoroughness is measured with an atomic force microscope (AFM). A 1 μm by 1 μm AFM scan is used to measure this quantity. The size of the scan defines the range of spatial frequencies sampled which cover the range from 1 μm^{-1} to approximately 0.01 μm^{-1}.

Test optic

A test optic was selected from a three mirror imaging system design of a 5x reduction ring field imaging system.[5] The design has a 1 x 25 mm ring field, a NA=0.1 and a resolution of 0.1 μm. The first mirror, M1, was selected as the test vehicle. The parent optic has a diameter of 0.28 m, a base radius of 1.79 m and an aspheric departure of 1.5 μm across the kidney shaped, 100 x 50 mm^2 clear aperture.

Tinsley Laboratories[6] fabricated the test optic from Zerodur. Zerodur is a low expansion glass produced by the Schott Glass Technologies, Inc. of Duryea, PA. The final finishing of the optic was done with computer controlled small tool polishing. During the fabrication process the figure error was measured interferometrically using a computer-generated-holographic (CGH) null. Tinsley Laboratories had demonstrated a capability to figure optics to a precision or repeatability of 0.6 nm rms. The M1 asphere was measured with the PSDI. Two interferograms were stitched together to measure the complete clear aperture. Figure 2 shows a map of the measured deviation from the design figure. The rms deviation is 0.95 nm rms.

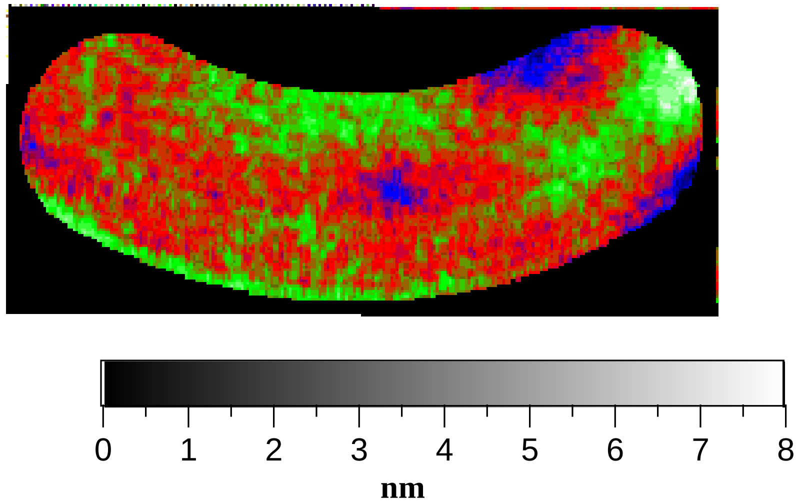

Figure 2: The residual error map measured in the clear aperture of the test optic using the

PSDI. The rms deviation is 0.95 nm.

The accuracy of the PSDI interferometer is estimated to be 0.6 nm rms. Subtracting the interferometer error from the measurement, we arrive at an estimated figure error of 0.7 nm rms across the clear aperture in good agreement with the Tinsley measurement using a CGH as a reference. This is the most accurate asphere ever fabricated.

The figure accuracy is short of the ultimate goal for EUVL, the 0.25 nm rms figure error discussed above. The metrology and fabrication capability demonstrated in this work can improve. Recent results reported by Kestner[7] have demonstrated a figuring precision of 0.3 nm rms on an aspheric optic. Sommargren has indicated that the PSDI may ultimately achieve 0.1 nm rms accuracy. A path may exists to produce EUVL aspheres with 0.25 nm rms figure error.

The surface roughness of the M1 optic was measured with a Digital Instruments 5000 AFM in the tapping mode using a diamond-like carbon (DLC) coated scanning tip. The DLC reduces measurement distortions due to electrostatic charging while scanning an insulating surface. One micron square areas were scanned at five sites on the optic. The average surface roughness was 0.25 nm RMS with a deviation of 0.033 nm rms. The magnitude of the deviation is equivalent to the noise level in the measurement.

During the course of this development several optics were fabricated. Steady improvements were made to the nanoroughness while maintaining a high level of figure precision. This indicates that controlling the characteristics of an optic in different spatial frequency ranges may be only weakly coupled.

Conclusions

We have demonstrated significant advances in the production of aspheric optics for EUVL. An optic has been fabricated with an aspheric departure of 1.5 µm, a rms figure error of 0.7 nm rms and a surface roughness of 0.25 nm rms. Further improvement is required in the figure and nanoroughness to reach high throughput near diffraction limited performance in an EUVL system. In addition, a recent analysis has been published quantifying the effects of midspatial frequency roughness on the imaging performance of EUVL optical systems.[8] This analysis indicates that the small angle scattering associated with the midspatial frequencies can have significant, detrimental impact on the imaging performance of EUVL systems. Controlling the midspatial frequency roughness will a key development area. We expect that optics for commercial EUVL systems will require control of the optical surfaces across the entire range of spatial frequencies from 0.01µm to the size of the clear aperture.

Acknowledgments

We would like to thank S. Baker and Digital Instruments Inc. for the AFM data. This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract no. W-7405-Eng-

48. This work was also funded by a Cooperative Research and Development Agreement (CRADA) T-0503-93-C.

References

1. D. G. Stearns, R. S. Rosen, and S. P. Vernon, "Multilayer Mirror Technology for Soft-X-Ray Projection Lithography," *Appl. Opt.* 32, 6952, 1993.
2. E. L. O'Neill, *Introduction to Statistical Optics*, Dover Publications, pp. 86-89 (1991).
3. G. E. Sommargren, "Phase-Shifting Point Diffraction Interferometer for Measuring EUV Optics," *OSA Topical Meeting on EUVL*, eds. D. R. Kania and G. Kubiak, 1996 (in press). (1996).
4. S. P. Vernon and S. L. Baker, "Recovery of EUV Lithography Substrates," *OSA Proceedings on Extreme Ultraviolet Lithography*, Vol. 23, eds. F. Zernike and D. T. Attwood, pp. 222-226 (1994).
5. J. H. Bruning, A. R. Phillips, D. R. Shafer, and A. D. White, "X-Ray Projection Lithography Camera," U.S. Patent 5,220,590 (1992).
6. Tinsley Laboratories, 3900 Lakeside Drive, Richmond, CA 94806.
7. R. Kestner, "Precision Asphere Fabrication and Metrology to Tolerance <1 nm RMS," *OSA Proceedings on Extreme Ultraviolet Lithography*, eds. D. R. Kania and G. Kubiak, 1996 (in press).

8. D. G. Stearns, et al., "Nonspecular Scattering in EUV Lithography: Determining the Specifications for Surface Finish *OSA*," *Proceedings on Extreme Ultraviolet Lithography*, eds. D. R. Kania and G. Kubiak, 1996 (in press).